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HOOP TENSION STRENGTH OF COMPOSITE GRAPHITE-ALUMINUM TUBES

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R. E. Ely

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by

R. E. Ely

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ABSTRACT

Composite tubes, consisting of a graphite liner confined in an aluminum sleeve, were subjected to hydrostatic burst tests at room temperature. The pressure at which the graphite liner failed is increased significantly by the reinforcing sleeve. The results are compared with a theoretical expression based on strength of material considerations.

CONTENTS

ILLUSTRATIONS

1 Introduction

Hot-gas ducts for rocket motors normally are lined with an insulating material which may serve also as a heat sink. Graphite is a good candidate liner material which has both a low density and erosion rate. Its short-time strength at elevated temperatures, though low in magnitude, surpasses the high-temperature strength of many metals.[1]

In typical applications, hot-gas ducts are subjected to high internal pressure loading which precedes extensive heating. Therefore, exploratory tests at room temperature were made to determine the fracture behavior of a graphite liner confined in a metallic sleeve. The test method employed caused the tube assembly to be subjected essentially to simple hoop tension stresses. To facilitate the analytical work, it was decided that the initial contact pressure or clearance between tubes should be zero. Since obtaining a zero clearance by mechanical means would be difficult, the tubes were machined with a known clearance and contact between the tube surfaces was accomplished by filling the annular void with an epoxy resin that was filled with metallic powder.

2. Test Materials and Method

All of the graphite tube specimens had a nominal inside diameter of 2.000 inches, an outside diameter of 2.625 inches, and a length of 8 inches (Figure 1). These specimens were machined from Graph-I-Tite, Grade G, which was received in the form of tubular stock: $1^{15}/_{16}$-inch inside diameter, $2^{3}/_{4}$-inch outside diameter, and 48 inches long. This graphite was fined-grained and had an apparent density of 1.88 grams/cubic centimeter. All cylindrical surfaces were paper polished after machining.

The aluminum sleeves, in which the graphite tubes were installed (Figure 1), were machined from 6061-T6 tubular stock. These sleeves were machined with wall thicknesses of 0.050, 0.075, and 0.100 inch; they also were 8 inches long and had a nominal inside diameter of 2.625 inches. To provide a known radial clearance between the graphite outside diameter and aluminum inside diameter surfaces, the aluminum sleeves were machined first and then the graphite tubes were machined and mated to a particular sleeve. Two sets of clearances were used. For tube assemblies with "small" clearances, the difference in inside diameter and outside diameter ranged from 0.002 to 0.004 inch; for the "large" clearances, this difference ranged from 0.009 to 0.012 inch.

Just before final assembly of the composite tube specimens, both the outside diameter surfaces of the graphite tubes and the inside diameter surfaces of the aluminum sleeves were coated with a thin layer of epoxy resin filled with aluminum powder. By volume, this coating consisted of 50 parts resin (EPI-REZ-510, Jones Dabney Company), 50 parts curing agent (EPI-CURE-855, Jones Dabney Company), and 100 parts aluminum powder (grade 101, Metal Disintegrating Company). The excess coating material was eliminated during assembly, which in most cases could be readily accomplished by manual means. For several of the assemblies with small clearances, however, a force of the order of 100 pounds was required to insert the graphite tube completely into the aluminum sleeve.

The composite tube specimens were potted in two batches which are referred to as Run Nos. 1 and 2. Identical procedures, which included a resin drying period of from 12 to 14 days before testing, were used in both cases.

The composite tube assembly, as well as graphite tubes individually, was subjected to internal fluid (water) pressure by using a plug fixture which utilized rubber O-rings for sealing (Figure 1). The distance between the centerlines of the O-ring grooves was $7\frac{1}{2}$ inches. In all cases, a thin coating of paraffin was applied to the graphite's inside diameter surface to prevent or minimize fluid penetration into the graphite. A simple piston and cylinder assembly driven by the crosshead motion of a universal tester was used for the pressurization source. The internal pressure history within the test specimen was sensed by a standard pressure cell and was recorded as a function of time (Figure 2); the peak pressures, also, were indicated on a bourdon tube-type gage.

Post-test inspections of the internal surfaces of the graphite tubes were made in order to reveal the failure cracks. In the inspection method, a TiO_2 developer and a red dye penetrant were utilized. These were applied after removing the paraffin coating. Pre-test inspections were performed only on the graphite specimens that were used during Run No. 2.

3. Analytical Method

The experimental fracture pressure results for the graphite tubes confined in metal sleeves were compared to predictions which were based on the strength of material consideration.

In Figure 3, Tube No. 1 corresponds to the graphite tube while Tube No. 2 refers to the metallic sleeve. The graphite tube will fracture in hoop tension at radius "a" when the internal pressure, p_i, reaches a given magnitude. Assigning the same radius, "b," to the outside diameter of Tube No. 1 and the inside diameter of Tube No. 2 implies that initially the two tubes were in contact and there were no prestresses. The contact pressure, p_o, was generated as the composite tube assembly was expanded. Further, it must be assumed that only elastic deformations took place and that both tube materials had isotropic properties. For the metal tube, the experiment can easily be designed so that only elastic deformation would take place. For the graphite tube, the assumption of elastic behavior to fracture conditions was not true but was reasonable. The assumption of isotropic elastic properties for the graphite was invalid. In this exploratory study, therefore, it was assumed that typical or average properties, with respect to various physical directions, could be employed.

With the above assumptions, the following expression for the internal pressure at which the graphite will fail in hoop tension may be derived readily from the radial displacement equations for thick wall cylinders:[2]

$$p_i = \sigma_1 \frac{\alpha - \mu_1 + (\beta + \mu_2)E_1/E_2}{1 - \alpha\mu_1 + \alpha(\beta + \mu_1)E_1/E_2} \qquad (1)$$

where

$\alpha = \dfrac{b^2 + a^2}{b^2 - a^2}$ (See Figure 3.)

$\beta = \dfrac{c^2 + b^2}{c^2 - b^2}$ (See Figure 3.)

μ_1 = Poisson's ratio for Tube No. 1

μ_2 = Poisson's ratio for Tube No. 2

E_1 = Young's modulus for Tube No. 1

E_2 = Young's modulus for Tube No. 2

σ_1 = Tensile strength of Tube No. 1

p_i = Internal pressure at fracture of Tube No. 1

Equation (1) for $\mu_2 = \mu_1$ and $E_2 = E_1$ reduces to

$$p_i = \sigma_1 \frac{c^2 - a^2}{c^2 + a^2} \qquad (2)$$

or the standard thick wall stress formula for a tube made of a single material and without a cylindrical interface.

4. Results

The internal pressures, at which the graphite tubes failed while confined in aluminum sleeves, were determined for 29 room temperature tests (Tables I and II). The time-to-fracture periods ranged from about 130 to 260 seconds; these periods were defined as the time required for the pressure to increase from 10 percent of the failure pressure to the failure pressure (Figure 2). The average (five tests) hoop tensile strength for the graphite tubes when not confined was 3157 psi which corresponds to an internal pressure of 838 psi at fracture. This tensile strength was greater than the vendor's value (2900 psi) as well as a value (2840 psi) reported for thin-wall tubes tested hydrostatically.[5] The primary fracture mode (Figure 4) was a single longitudinal crack.

The fracture pressures for tube assemblies with small initial clearances were compared with theoretical curves in Figure 5. These curves were constructed by using Equation (1) and the following values:

a = 2.000 inches

b = 2.625 inches

c = variable

E_1 = 1,500,000 and 1,800,000 psi

E_2 = 10,000,000 psi

μ_1 = 0.10

μ_2 = 0.33

σ_1 = 3157 psi

The elastic modulus given by the vendor for the graphite was 1.8×10^6 psi, and it was assumed to be with-the-grain. The 1.5×10^6 psi was an arbitrary value and one which probably was less than an average value for the with- and across-grain moduli. The average modulus, 1.3×10^6 psi, for ATJ graphite, for example, was only about 10 percent less than the with-grain modulus, 1.45×10^6 psi.[4]

The Poisson's ratio for the graphite, 0.10, was a typical value.[5] To determine the significance of using this value, failure pressure calculations, also, were made when using ratios of zero and 0.2. The resulting pressure magnitudes only varied about 2 percent from the value obtained when using a ratio of 0.10.

The agreement between the results and theory was reasonable for the tube assemblies with small initial clearances (Figure 5). Several of the failure pressures exceed significantly the predicted values. This behavior might be attributed to the fact that the graphite was prestressed compressively. As indicated previously, force was required in some cases to insert the graphite tubes completely into the aluminum sleeves; volumetric shrinkage of the filled-resin while curing would have been small, say, 2 percent. The graphite tube failure modes were primarily a single crack which was readily observable; this mode also was verified by the red dye inspection method for Test No. T-1112 where the failure pressure was quite low (Table I).

The failure pressures obtained when using large initial clearances (Figure 6) in general were reduced in magnitude, and several of the values were quite low. In Table II, the three low values associated with triple cracking were not plotted in Figure 6. These data were discarded because pre-test inspections of two untested graphite tubes revealed such damage, and this damage was attributed to excessive chucking pressure with a 3-jaw chuck during machining. The other two low values, Test Nos. T-1119 and T-1127, were not discarded nor can they be explained since these graphite tubes failed with the usual, single crack.

Figure 7 shows theoretical curves for the hoop tension stress in the aluminum sleeve immediately before and after the graphite tube fails. The lower curve was constructed by calculating stress values by means of the thick-wall formula for the contact pressures predicted by Equation (1). The maximum stress developed in the aluminum sleeve immediately before the graphite fails was of the order of 12,500 psi for all wall thicknesses. After the graphite tube fails (it was assumed that only the aluminum sleeve is available for containing the fluid pressure) the aluminum would yield for wall thickness of about 0.040 inch and less.

5. Conclusions

The results indicated that it is advantageous to use the load carrying capacity of both components of a graphite-aluminum composite tube at room temperature. To insure satisfactory performance, the graphite liner should be free of flaws and contact between the liner and outer sleeve must be positive. Increases in performance could be obtained by intentionally prestressing compressively the graphite tube. Prestressing would be essential for high-temperature applications since the thermal expansion of the graphite is much less than for aluminum. Other factors to be considered would include the thermal stresses in the sleeve material and the heat sink capabilities of the complete assembly. In future studies, attention should be given to the high-temperature performance of composite tubes with controlled prestressing. The prediction theory would have to be modified to account for thermal stresses and the anisotropic properties of the liner material; the elastic constant of this material also should be evaluated thoroughly.

Table I. Fracture Pressures for Composite Tubes with Small Clearances

Test No.	Aluminum Wall Thickness, mils	Pressure at Fracture, psi	Fracture Time (Estimated), sec	Run No.
T-1104	50	1880	220	1
T-1105	50	*1125	198	1
T-1106	50	1500	246	1
T-1120	50	1755	141	2
T-1121	50	1390	129	2
T-1122	50	1420	156	2
T-1111	75	2130	148	1
T-1112	75	†875	---	1
T-1123	75	1645	148	2
T-1124	75	1775	168	2
T-1125	75	2100	161	2
T-1116	100	1940	193	1
T-1117	100	2170	---	1
T-1102	100	2250	189	1

*Pre-test inspection revealed flaw on inside diameter surface of graphite tube.

†Post-test inspection revealed single longitudinal failure crack in graphite tube.

Table II. Fracture Pressures for Composite Tubes with Large Clearances

Test No.	Aluminum Wall Thickness, mils	Pressure at Fracture, psi	Fracture Time (Estimated), sec	Run No.
T-1107	50	*610	---	1
T-1108	50	1460	242	1
T-1109	50	1660	261	1
T-1126	50	1500	---	2
T-1127	50	†860	---	2
T-1128	50	*530	---	2
T-1113	75	1610	168	1
T-1114	75	1520	174	1
T-1115	75	1880	184	1
T-1129	75	*700	---	2
T-1130	75	1800	---	2
T-1131	75	1800	---	2
T-1118	100	2050	---	1
T-1119	100	†1300	---	1
T-1103	100	1660	---	1

*Post-test inspection revealed three longitudinal cracks in graphite tube spaced at approximately 120 degrees.

†Post-test inspection revealed single longitudinal failure crack in graphite tube.

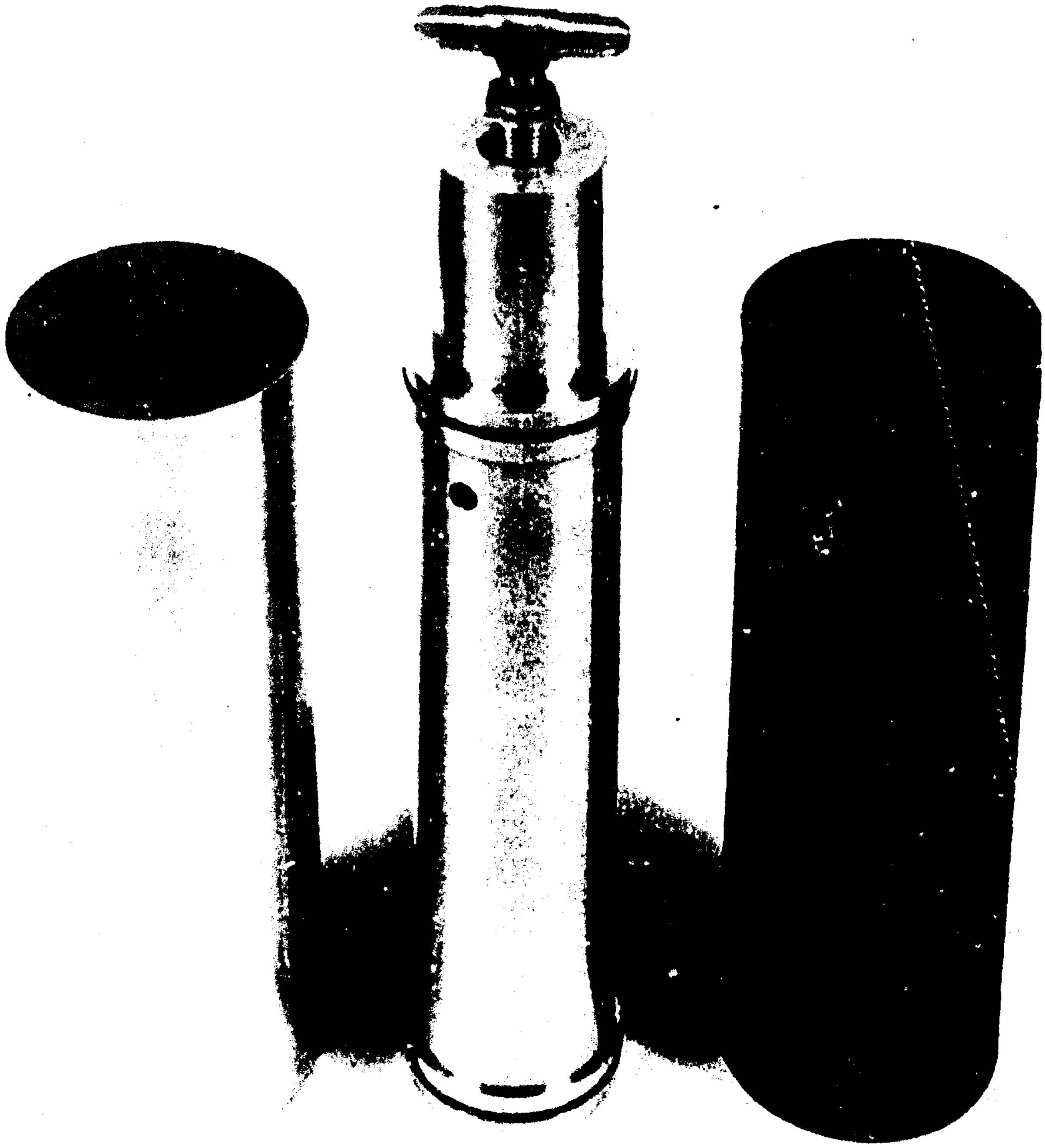

Figure 1. Test Specimens and Plug Fixture

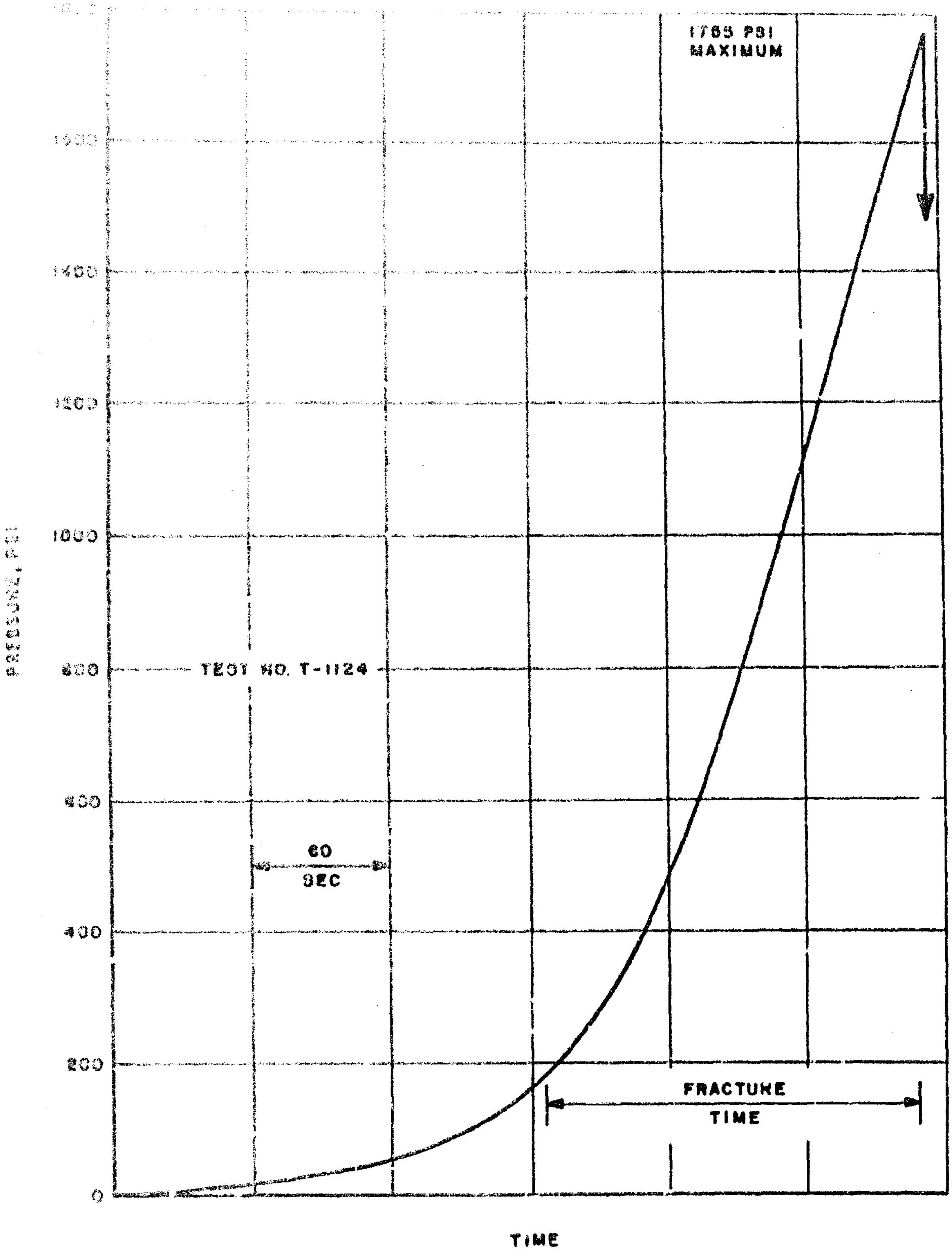

Figure 4. Pressure-Time Record for Composite Tube Test

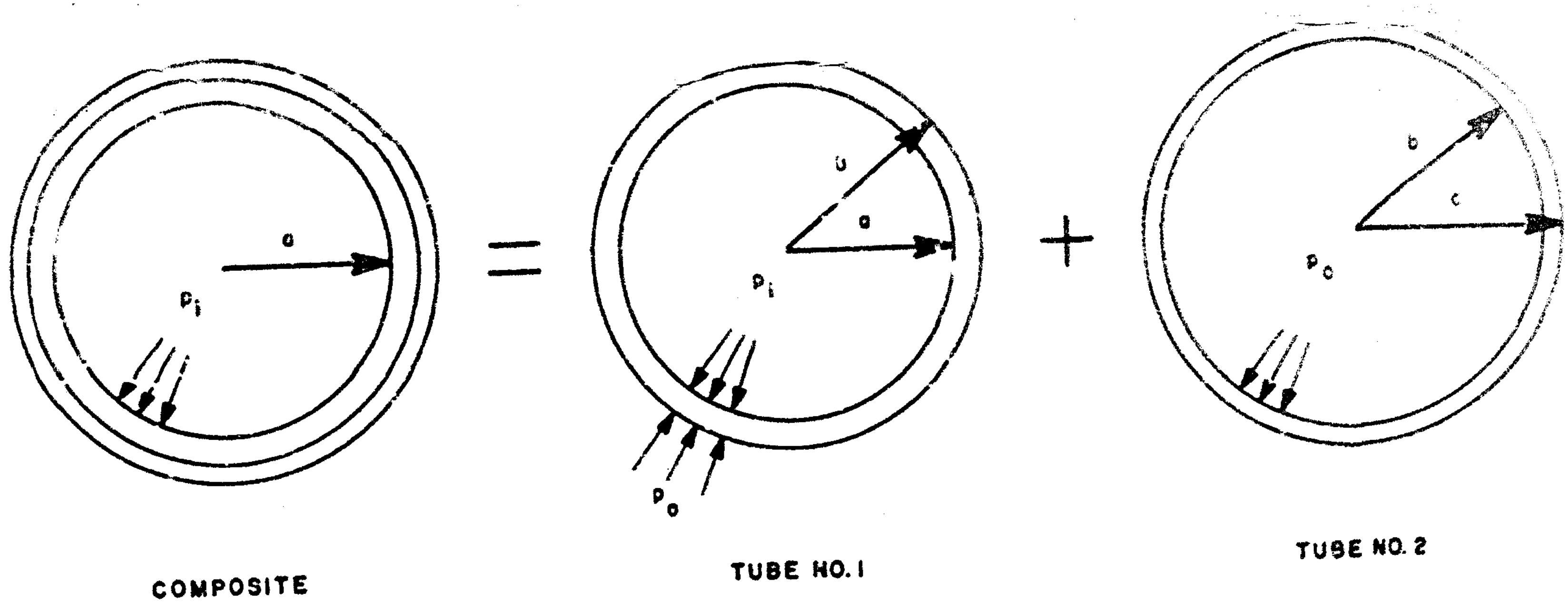

Figure 3. Nomenclature

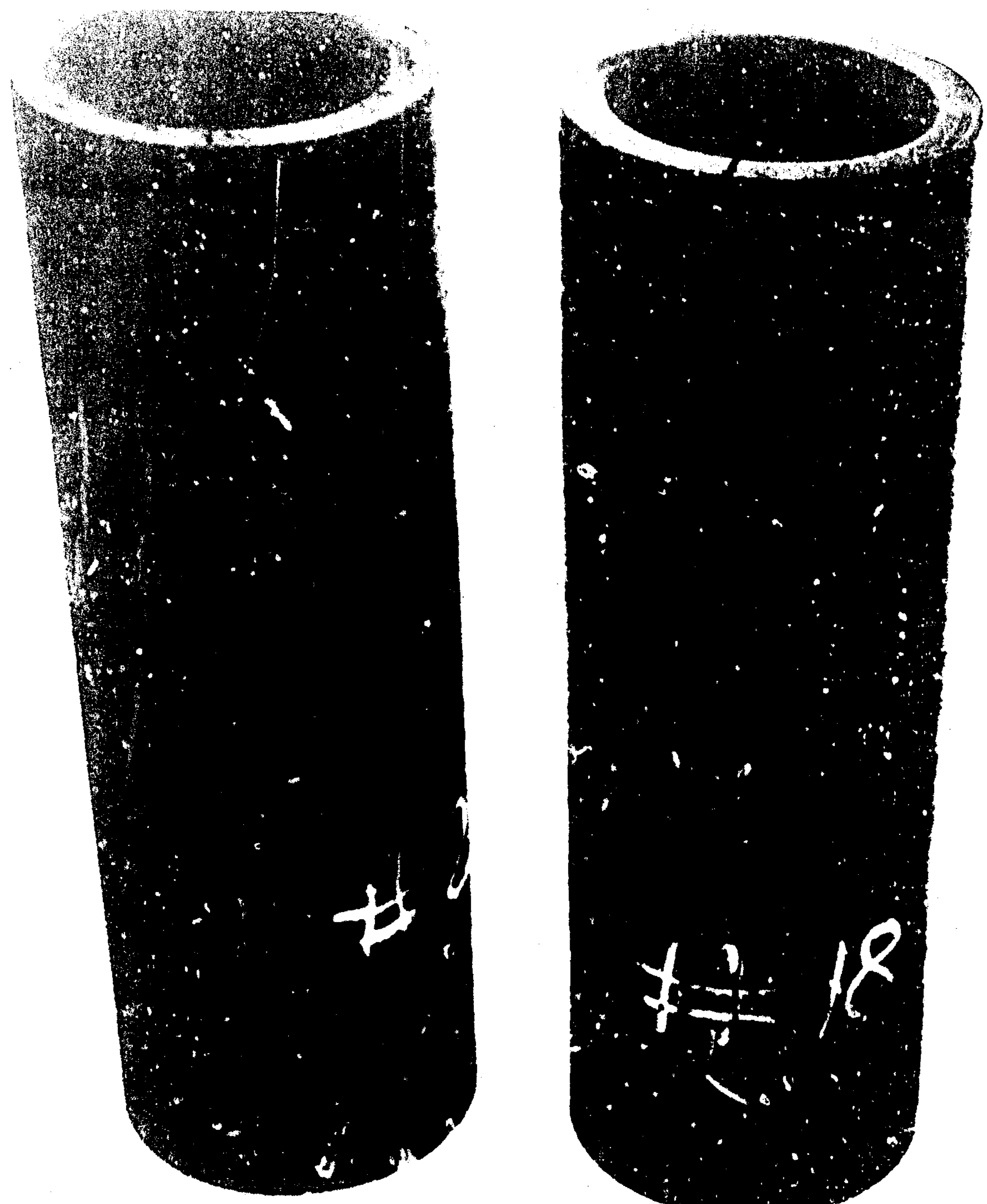

Figure 4. Fractured Graphite Tubes

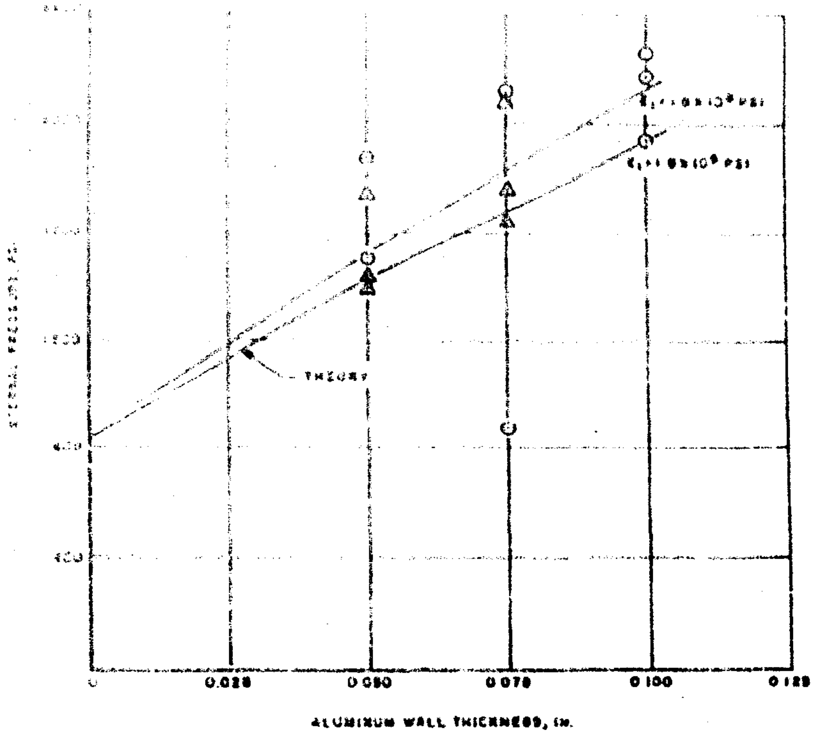

Figure 5. Fracture Pressure of Confined Graphite Tubes with Small Initial Clearances

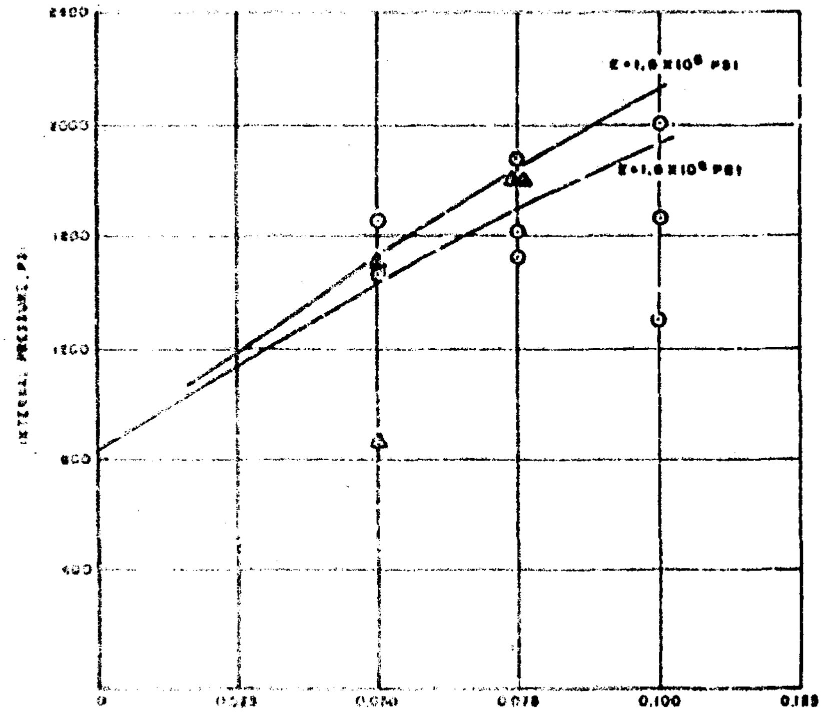

Figure 6 Fracture Pressure of Confined Graphite Tubes with Large Initial Clearances

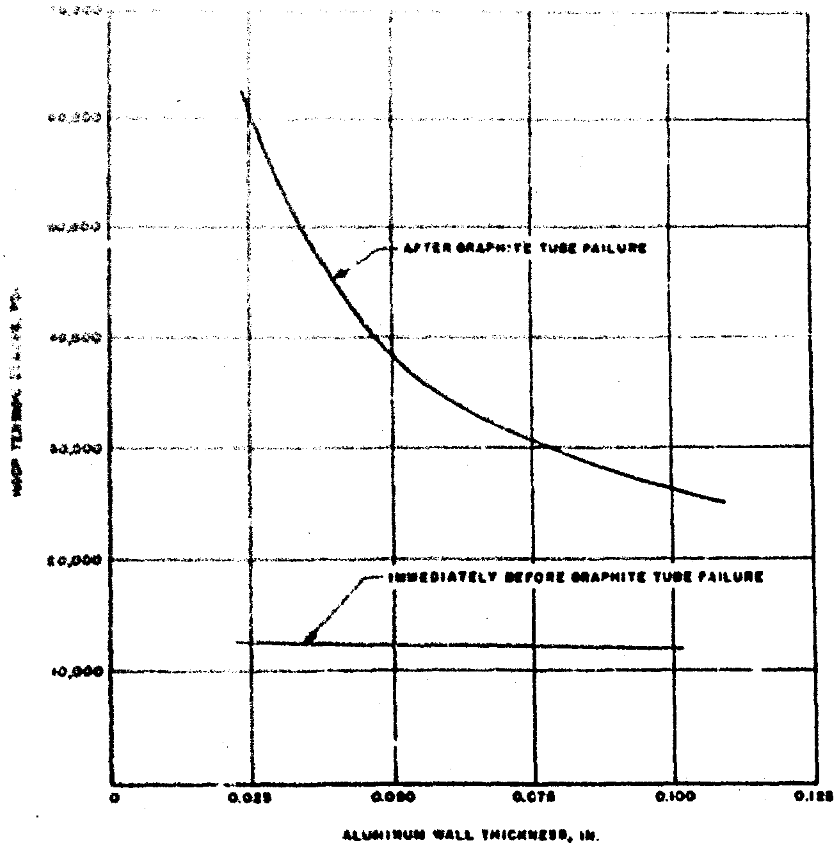

Figure 7. Stress Levels in Aluminum Sleeve at Graphite Tube Failure Pressures

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